

# THE STUDY OF THE X-RAY EMISSION FROM THE ACCRETING BLACK HOLES AND NEUTRON STARS

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## Summary

The thesis studies the X-ray emission from the Galactic compact objects (accreting neutron stars and black holes), using mainly the RXTE data.

In particular following results have been included: spectral evolution of X-ray transients GRS 1739–278, XTE J1755–324, GS 1354–644, XTE J1748–288; the outburst and detailed spectroscopy of the anomalous X-ray Novae XTE J0421+560; study of the outburst of the millisecond pulsar SAX J1808.4–3658 and stability of its spectrum; study of the SAX J1808.4–3658 pulse profile and relativistic distortions of the profile, the linear velocity of the emitting area on the surface of the neutron star SAX J1808.4–3658, inferred from our simplest model is about  $\sim 0.1$  c and the neutron star radius  $\sim 13$  km; frequency resolved spectroscopy and its application to the hard state of Cyg X-1 and GX 339-4, correlations of the spectral and timing properties for Cyg X-1, GX 339-4 and possible connection to the disk-spheroid model of the accreting flow in the vicinity of the black hole.

***The first part*** of the thesis briefly describes the RXTE, GRANAT and MIR/KVANT/TTM instruments and observational procedures.

***The second part*** consists of 4 chapters, which describe the outbursts of the X-ray Novae.

*The first chapter* of the second part describes the outburst of X-ray Novae GRS 1739–278 in Mar.–May 1996 in details. We used RXTE and MIR/KVANT/TTM data in our analysis. It is shown, that on the beginning of the outburst (before the primary maximum) the spectrum of the source had very weak soft component, its contribution to the 2–20 keV flux did not exceed 50% (TTM telescope result). For a comparison, the usual value for the soft component contribution for the High State spectra is about 80–90%. The analysis of the subsequent observations of RXTE showed the change of the “inner disk temperature”, that can not be explained by the standard disk theory with the constant inner radius. We propose, that the electron scattering plays the important role in the forming the emergent spectrum in GRS 1739–278.

*The second chapter* describes the outburst of XTE J1755–324 in 1997 using RXTE and GRANAT data. The RXTE observations showed the sequence of standard states of X-ray

Novae : High (strong soft component, weak aperiodic noise) and Low (hard spectrum and significant chaotic variability). The peculiar hardening was detected close to the tertiary maximum.

*In the third chapter* we explore the outburst of the hard X-ray Novae GS 1354–644 in the end of 1997 – beginning of 1998. It is shown, that the energy spectrum of this Nova can be described by the emission of the comptonized cloud with the temperature  $\sim 20$  keV with reflected component. The analysis of aperiodic variability of X-ray flux showed, that it can be represented by the sequence of the exponential shots with two (in the first two observations - three) different characteristic decay times. The analysis of the density of a probability of X-ray flux, integrated over 16 sec bins, allowed us to estimate the shot rate value of the long shots.

It was shown that the dependence of the rms of the aperiodic variability on the photon energy can not be explained by the compton upscattering process. It was shown that majority of the black hole systems in the hard state demonstrate the decrease of the rms value with the photon energy, while the neutron star systems show the opposite trend – the increase of the rms with the photon energy.

*The fourth chapter* of the second part describes the outburst of the third Galactic microquasar XTE J1748–288 in 1998. We detected the sequence of the standard states : Very High, High and Low. During the Very High state observations the source had very weak soft component, similar to that of GRS 1739–278 (see Chapter 1 above).

In ***the third part*** of the thesis we describe the outburst of the very peculiar source – XTE J0421+560/CI Cam in 1998. It is shown that the emission of the source originates in the hot optically thin plasma cloud. We show that the source do not demonstrate any aperiodic variability (in the first observations the  $2\sigma$  upper limit on the rms value is about 0.8%). The evolution of the source spectrum is described in details. The mass of the emitting object and its radius are estimated. We detected the displacement in the position of the broad emission feature (from 6.53 keV to 6.61 keV). we propose that the apparent displacement of the centroid can be caused by the presence of 6.4 keV fluorescent line in the spectra. We detected the additional emission feature at the energy  $\sim 8$  keV (most likely – the thermal lines  $K_\beta$  Fe and  $K_\alpha$  Ni)

In ***the fourth part*** of the work, that consist of two chapters, we analise millisecond pulsar-burster SAX J1808.4–3658.

*The first chapter* of this part devoted to the outburst of SAX J1808.4–3658. It is shown that the energy spectrum of the source ( $I_\nu \sim \nu^{-2}$ ) was approximately the same throughout the outburst, while the energy flux changed by the two orders of magnitude. Assuming that the rapid drop of the X-ray light curve of the SAX J1808.4–3658 is caused by transition of the source to a propeller regime we estimated the star magnetic field.

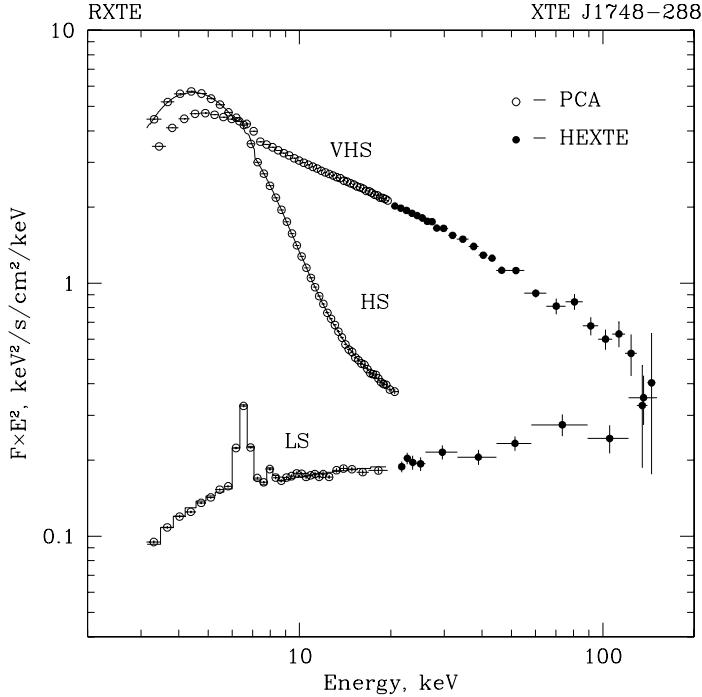


Figure 1: Typical energy spectra of XTE J1748-288 in the different states. The white and black circles show the PCA and HEXTE data respectively.

$$B \sim 3 \cdot 10^7 M_{1.4}^{1/3} R_6^{-8/3} \left( \frac{L_x}{10^{35}} \right)^{1/2} \text{ G}$$

(here  $M_{1.4}$  – the neutron star mass in  $1.4M_{\odot}$ ,  $R_6$  – the radius of the star in tens of km,  $L_x$  – the transition luminosity). However, the rapid drop of the X-ray flux can also be caused by the disk instabilities, analogous to that observed in cataclysmic variables. We propose, that the hard spectrum can originate in the radiation dominated shock near the neutron star surface.

In the *second chapter* of the fourth part we analyze the pulse profile of the millisecond pulsar SAX J1808.4–3658. It is shown that the observed difference of the pulse profile in the energy  $<4$  keV (in the energy spectrum at these energies the soft component dominates, the soft component can be approximated with the black body spectrum) from the simple sinusoid can be explained by the influence of the relativistic aberration (Fig. 3). We propose the simplest model of the observed distortions. This model allowed us to estimate the emitting region linear velocity and, consequently, the radius of the

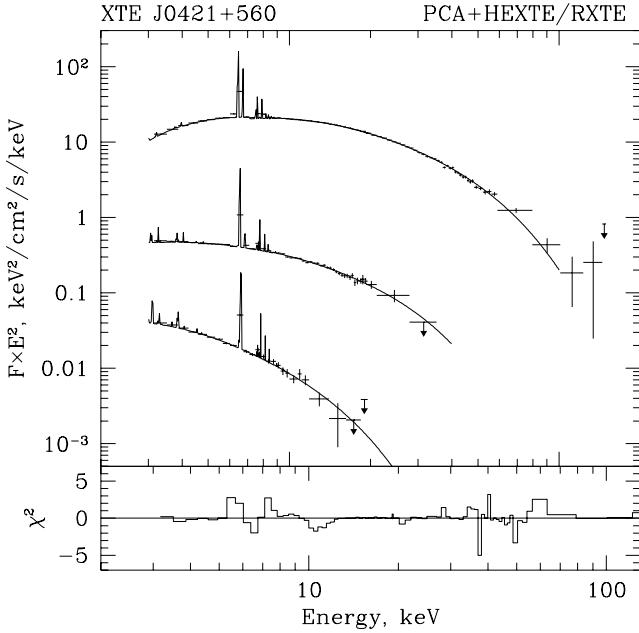


Figure 2: Spectra of XTE J0421+560 in different luminosity states. The most luminous one – on Apr. 1, 1998, the middle one – Apr. 3, 1998, the weakest – Apr. 9, 1998. On the lower panel the  $\chi^2$  curve for the upper spectrum is presented. Not all of shown lines are seen by PCA, a number of emission lines caused by *meka* model (see text).

neutron star:  $R \sim 13\text{--}19$  km. It is shown the allowance for Schwarzschild metric further improve the pulse profile approximation.

In ***the fifth part*** we explore the aperiodic variability of the well known Galactic black hole candidates Cyg X-1 and GX 339-4. We propose the frequency resolved spectral analysis for the exploration of the variability of the various spectral component. With the help of this method we show that the variability of the reflected component in the spectra of Cyg X-1 and GX 339-4 is strongly damped at the frequencies higher than 1–10 Hz. We propose simplest explanations of this behavior. In particular, the suppression of the high frequency variability can be caused by the influence of the large size of the reflecting accretion disk.

***The sixth part*** of the thesis is devoted to the systematic analysis of the energy spectra and the characteristics of the aperiodic variability of Cyg X-1 and GX 339-4 in the hard/low spectral state. We detected tight correlations of the parameters of the energy spectra and the power density spectra. The increase of the characteristic frequency on the power density spectra (the frequency of the first break or the QPO frequency) accompanying by the increase of photon index  $\alpha$  of the primary power law and by the increase of the reflection amplitude  $\Omega/2\pi$ . It is commonly accepted now, that the accretion

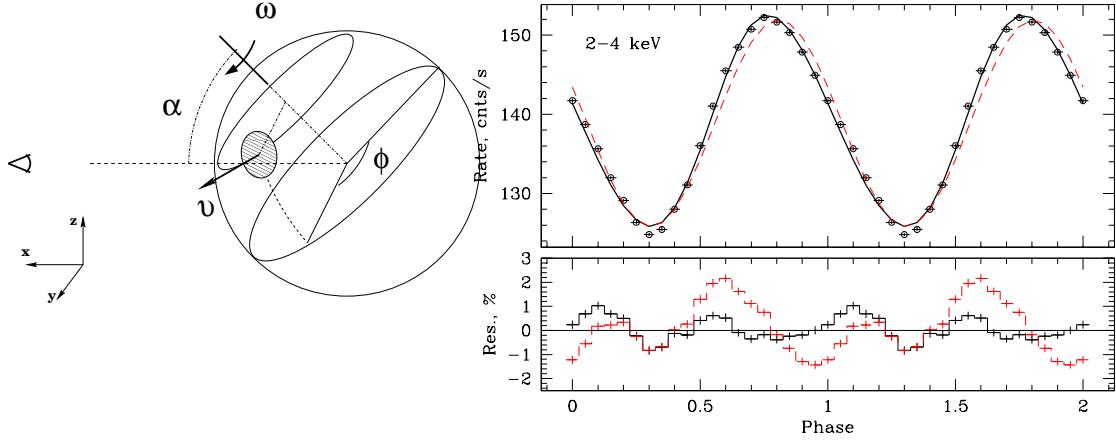


Figure 3: The pulse profile of SAX J1808.4-3658. The solid line shows the approximation of the observed pulse profile by our model with the relativistic distortions. Dashed line shows the approximation by the simple sinus. Lower panel shows the residuals in percents. Left picture shows the simplest geometry used in the model.

flow in the black hole systems in the hard/low spectral state consist of the hot inner cloud, where the comptonized component originates, and the surrounding cold accretion disk (see e.g. Fig.5). The observed correlations can be understood if we assume that the characteristic frequency in the PDS is connected with the keplerian frequency on the inner edge of the cold accretion disk. In this case the decrease of the inner radius will result in the increase of the characteristic frequency, the increase of the reflection amplitude and (because of the feedback) the total softening of the primary spectrum (see Fig.5). It is shown that the “ $\alpha - \Omega/2\pi$ ” dependence continues to the soft state.

The full variant of the thesis can be found in  
<http://hea.iki.rssi.ru/~mikej/thesis/dis.html>

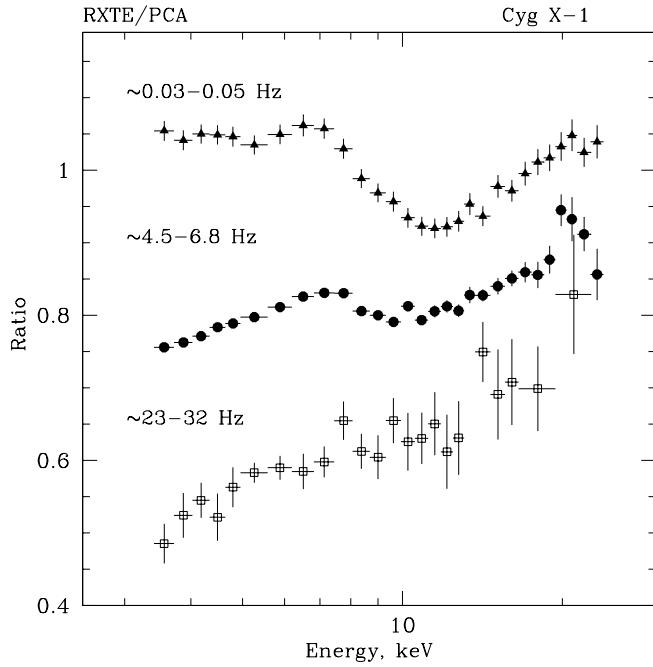


Figure 4: The ratio of the energy spectra of Cyg X-1 in different frequency bands to a power law model with photon index  $\alpha = 1.8$ . Spectra corresponding to 0.03-0.05 Hz and 23-32 Hz were rescaled for clarity.

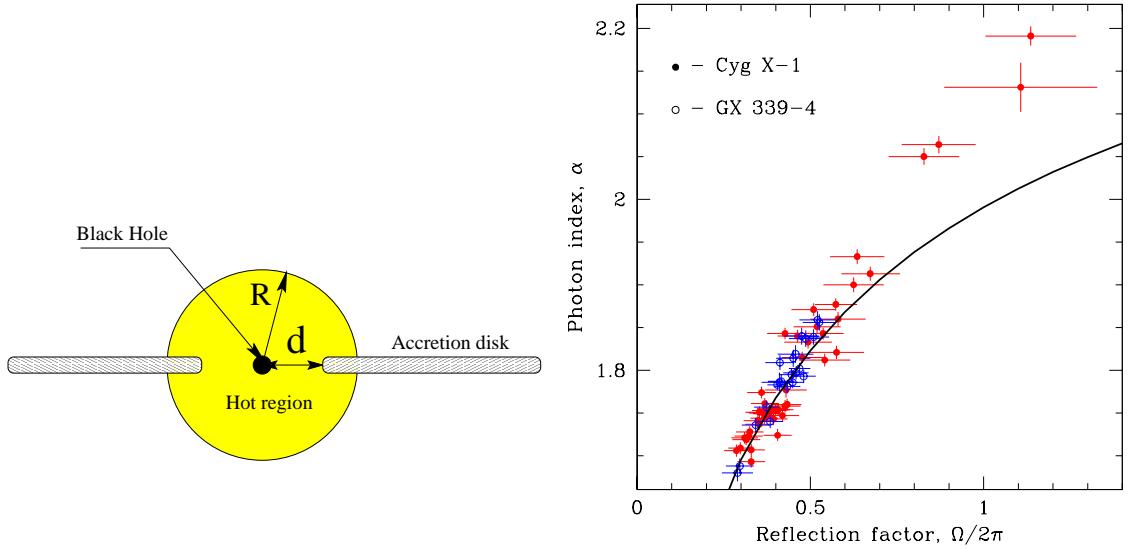


Figure 5: **Left panel:** The assumed geometry of the accretion flow in Cyg X-1 and GX 339-4 in the low spectral state **Right panel:** The approximation the correlation  $\Omega/2\pi - \alpha$  observed for Cyg X-1 and GX 339-4. The solid line shows the used simplest model.